TRANSIENT VOLTAGE SUPPRESSION

CROSS-REFERENCE TO RELATED APPLICATION

The subject matter of this application is related to the subject matter of British Patent Application No. GB 0030844.5, priority to which is claimed under 35 U.S.C. § 119 and which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to transient voltage suppression in electrical systems.

2. Description of Related Art

In some installations of electrical equipment, a fixed connection to the public electricity supply is not possible because the site does not have a utility connection (e.g. it may be in a geographically remote area or a construction site) or because the installation is mobile (e.g. it is on an automobile, a vessel or an aircraft). In these situations, the system is typically supplied by an alternator driven by a prime mover, such as an internal combustion engine, steam or gas turbine, etc. A storage battery is typically provided to store sufficient energy to start the prime mover and is recharged by the alternator

when there is sufficient generated capacity. The battery can also be used to supply the electrical load when the generator has insufficient output.

The loads on an electrical system may be purely resistive, e.g. heaters, or can be motors or actuators, but at least one of the loads is typically the storage battery.

Since the alternator has a maximum output that is of the same order of magnitude as the consumption of the loads, adding or removing one of the loads can produce significant voltage transients across the supply rails. While it is the task of a voltage regulator to suppress these transient disturbances and maintain the desired steady-state output from the alternator, there is a significant limit to the speed at which it can respond to changes in demand. This limit arises from the facts that the field circuit of a typical alternator has a relatively long time constant (mainly due to the use of unlaminated pole pieces in the rotor construction) and that the voltage regulator is normally a single-quadrant device, so it cannot compensate well for fast transients. To prevent these transients from causing damage to other equipment, other suppression measures have to be adopted. One approach is to connect a transient voltage suppressor across the rails to absorb transient overvoltages and dissipate the associated energy.

The transient voltage suppressor is often rated to cope with the worst transients likely to occur on the rails. These can be when the battery is

disconnected while drawing charging current from the rails – a condition known as "load dump." It may be the result of intentional disconnection by the user or of unintentional disconnection through failure of a connector. This transient can be severe: for example on a nominal 12V system the voltage can rise to 80V and the pulse can have a duration of over 300 msec. Standards have been drawn up for equipment designed for operation on a bus subject to such transients. For example, ISO 7637 defines a test pulse based on a load dump. However, rating the transient voltage suppressor to cope with the load dump condition usually results in a component of significant cost, whose capabilities are seldom, if ever, required. While this is technically an effective solution, it is not cost-effective.

Other solutions that are known are to insert a relay in series with the rail and to open it as the transient raises the voltage above a particular threshold. If the relay operates quickly enough, this arrangement gives good protection but has the disadvantage that the supply to all the loads, some of which may be safety critical, is interrupted. A further solution is to rate the loads to survive the higher bus voltage, but this is seldom cost-effective, especially in the high-volume production of, for example, automobile electrical systems.

SUMMARY OF THE INVENTION

Embodiments of the invention allow at least some of the energy in a transient voltage to be absorbed without using an expensive, highly rated, voltage suppressor or interrupting the supply to other loads. It has been recognized that the phase or phases of certain electrical machines can be used to absorb energy in a voltage transient. Thus, by detecting the onset of such a transient, it is possible to connect such a machine to absorb the energy. The electrical machine itself is generally available to perform its normal duties but can be connected to perform this additional task. Electrical machines with a single phase or independent phases, i.e. physically and electrically isolated from each other, such as switched reluctance machines, can be used advantageously in this way to connect one or more phases simultaneously or in sequence, depending on the severity of the transient.

According to embodiments of the invention, the same switch arrangement that is used to operate the electrical machine can be used to connect the or each phase to absorb the energy in the transient.

The duration for which the phase or phases is/are connected to absorb the transient can be fixed or based on monitoring the transient itself. Similarly, the switching on of the or each phase can be at each and every voltage transient or, preferably, it is subject to a threshold only above which it is used.

The operation of the electrical machine can be carried on normally until the transient is detected, at which time the normal operation is overridden to address the transient voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention can be put into practice in various ways, some of which will now be described with reference to the accompanying drawings, in which:

Figure 1 shows an example of an electrical system according to an embodiment of the invention;

Figure 2 shows the connection of one phase winding in a typical power converter; and

Figure 3 shows a typical prior art inverter and induction motor.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring to Figure 1, an alternator 10 is driven by an internal combustion engine 12. The alternator 10 is of the conventional 3-phase claw-pole, homopolar type, with its single field winding 14 supplied via slip-rings 16 from a simple voltage regulator 18. The alternating output from stator windings 20 is rectified by a diode bridge 22 and provides a voltage bus with a large DC component and superimposed ripple on rails 24/26. Various loads 28/30 are connected across the rails 24/26 at the output of the diode bridge 22.

One of these loads may be a storage battery. A transient voltage suppressor 31 is also connected across the rails 24/26 to absorb the energy in transient pulses. As discussed above, however, the suppressor 31 would have to be highly rated to cope with the rare, but potentially catastrophic, event of a load dump. As described below, the invention removes all or part of the burden on the suppressor 31.

Also connected in parallel with the loads 28/30 is a power converter 32 having a switching circuit for each phase winding 34 of a switched reluctance machine 36. The characteristics and operation of switched reluctance systems are well known in the art and are described in, for example, "The characteristics, design and application of switched reluctance motors and drives" by Stephenson and Blake, PCIM'93, Nürnberg, 21-24 June 1993, incorporated herein by reference. The switching of the power converter by an electronic control unit 38 must be correctly synchronized to the angle of rotation of the rotor for proper operation of the drive, and a rotor position detector 40 is typically employed to supply signals corresponding to the angular position of the rotor. The rotor position detector 40 may take many forms, including a physical sensor as illustrated, or a software algorithm. Its output may also be used to generate a speed feedback signal.

A switching circuit of the power converter 32 for one phase of a polyphase system is illustrated in Figure 2, although an identical circuit would

be similarly connected between the rails 24/26 for each of the three phases 34 of the machine shown. Many different power converter topologies are known, several of which are discussed in the Stephenson paper cited above. In the circuit of Figure 2, the phase winding 34 of the machine is connected in series with two switching devices 50 and 52 across the positive and negative rails 24 and 26. Rails 24 and 26 are collectively described as the "DC link" in respect of the converter. Energy recovery diodes 54 and 56 are connected to the winding to allow the winding current to flow back to the DC link when the switches 50 and 52 are opened. A capacitor 58, known as the "DC link capacitor," is connected across the DC link to source or sink any alternating component of the DC link current (i.e. the so-called "ripple current") that cannot be drawn from or returned to the supply. In practical terms, the capacitor 58 may comprise several capacitors connected in series and/or parallel and, where parallel connection is used, some of the elements may be distributed throughout the converter. The circuit is known as the two-switch-per-phase type and is connected, in accordance with the embodiment of the invention, across the rails 24/26 from the diode bridge 22.

Referring back to Figure 1, the mechanical output from the shaft 60 of the motor 36 is connected to a mechanical load 62. The switching performed by the switching circuits of the power converter 32 is controlled by the controller 38 based on a demand input 64, and current and rotor position

feedback from the sensors 66/40. A voltage threshold detector 68 is connected across the output of the diode bridge 22. In the presence of a voltage on the output rails 24/26 of the diode bridge 22 above a given magnitude (as described below), the detector 68 outputs a signal to the controller 38, which closes the switches of all or some of the phases of the polyphase machine 36 to absorb the energy in the transient voltage to protect the loads 28/30.

Embodiments of the invention make use of the properties of a switched reluctance drive system to protect both their own power electronics and other equipment from transient voltage disturbances. Their ability to do this stems from two aspects. Firstly, the phase windings of the machine are physically and electrically isolated from each other. Secondly, the particular topology of power converter used for such isolated phases enables the phases to be switched independently of each other. A significant point to note in the switch topology for one phase illustrated in Figure 2, i.e. the 2-switch-per-phase circuit, is that the switches 50/52 are in series with the winding. This is a feature common to the circuits typically used for these switched reluctance machines. Other such circuits are described in the paper by Stephenson and Blake cited above and these are all in contrast to the inverter topology used for other variable speed drives using induction, synchronous or permanent magnet motors (shown in Figure 3) where the two switches for a phase leg, e.g. S_1 and S_6 in Figure 3, are in series directly across the DC bus without any interposing winding.

Solid-state switches can survive much greater voltage transients when they are closed than when they are open. However, it is a consequence of the layout of the inverter shown in Figure 3 that when, say, the switches S_1 and S_2 are closed to connect the winding RS to the supply, switches S_6 and S_3 are automatically exposed to the full supply voltage, including any transients on the supply. In the case of the switched reluctance machine converter circuit of Figure 2, *both* switches in a phase leg are closed together when the phase is conducting. Because the inductance of the phase winding is placed across the rails 24/26, the current rises relatively slowly. By contrast, if the two switches of a phase leg of the inverter in Figure 3 are closed together, they represent a short circuit across the rails and the rise in current is very rapid and generally destructive to the switches.

Hence, if the switches 50/52 of a phase in a switched reluctance system are closed when an over-voltage transient occurs on the voltage bus supplying the drive system, the current in the phase will rise relatively slowly but, because they are closed, the switches will be much more likely to survive the transient. Embodiments of the invention lie in switching on at least one phase of the switched reluctance converter when the onset of a transient is detected. Preferably the switches of each phase are closed, thus protecting them from the transient. This brings a second benefit, in that the switched reluctance machine absorbs energy from the transient, thus reducing its magnitude and

protecting other equipment on the same supply rails.

The effect of this switching action on the machine is somewhat complex, since it depends on, *inter alia*: the per unit resistance of the phase windings (which in turn depends on the relative machine size); the pole arc geometry; the coupled load; the inertia of the load; and on whether the machine was initially rotating. For a small machine, with a high per unit resistance, the current will likely be limited by the phase resistance, whereas in a larger machine the resistive voltage drop will be negligible. In general, the torque developed by the machine, when all the phases are switched on simultaneously, is small compared with its rated torque and, at some rotor angles, will be zero. If the rotor is initially at rest, and in the absence of any significant load torque, the rotor will therefore turn a maximum of half a revolution and remain there. In the presence of load torque, the machine may not rotate at all. If the machine is initially rotating, it is likely to gradually come to rest while the current rises in the phase windings. It is therefore possible to apply this method whether or not the machine is initially rotating.

The effect of dumping energy in the switched reluctance machine is generally insignificant as far as the machine is concerned, leading only to some additional heating in the windings, but the use of the machine to absorb energy is very significant as far as the transient voltage suppressor 31 is concerned, allowing a much reduced rating for this component and hence reduced cost.

It would be possible, in theory, to remove the transient voltage suppressor 31 altogether and rely on the ability of the switched reluctance machine and its switching circuits in the power converter 32 to absorb the transients above the set threshold. As a practical matter, however, to do so would mean that the performance of the switched reluctance motor would be too frequently undermined by the perturbations it would cause. Thus, the transient voltage suppressor 31 is retained but with a reduced rating to handle the relatively brief, lesser transients that are likely to occur most frequently. This leaves the switched reluctance motor to cope with the larger transients that are likely to occur considerably less frequently. Reference is made above to the events giving rise to potentially major load dump transients, e.g. disconnection of the battery. If this happens at all, it will be only very rarely. The switched reluctance motor system performs its own motor task for the vast majority of the time, but is available to absorb the relatively large energy of such a major voltage transient of relatively long duration if and when it occurs.

To implement the invention, the voltage threshold in the detector 68 is set to a level under which all the equipment on the DC bus can operate without damage. For a 12V system (typical in an automobile), this could be around 24V. During voltage transients up to this threshold, the voltage regulator 18 will attempt to compensate by modulating the field current in known manner, and to the extent that it fails to hold the voltage, the loads will accept the

transients and survive them. When the voltage rises above the set threshold, or rises above the threshold for a predetermined period, the controller is caused to close all switches 50/52 in the converter 32 and waits until the combination of the load presented by the switched reluctance machine, the voltage regulator 18 and the transient suppressor 31 reduces the voltage below the threshold. The switches 50/52 can then be opened again, either simultaneously or in a sequence. The simplest method is to open them all simultaneously, though on some systems this may allow the voltage across the rails 24/26 to rise again as the energy sink is lost. A more sophisticated method is to open them one phase leg at a time, with a time delay between each phase. This will reduce any tendency for the rail voltage to oscillate. The time delay can be predetermined between switch openings or it may be based on monitoring the decline in the transient itself, such that the switches are opened at set points in the fall of the voltage transients. A yet further method is to open the phases in a sequence beginning with the one that has the highest current. This method is preferred, since it reduces the risk of overcurrent in the phases (and hence potential damage to the switches 50/52) but preserves an energy sink for the longest possible time.

Other variants of the method include turning on the phases in a sequence as the voltage rises over a series of thresholds; timing the length of time the switches are closed and opening them at a time calculated, say, to be less than

the time the current would take to rise to a value which would be injurious to the switches; modulation of the switches after the current has risen to a predetermined level to keep the phase current within a safe level or to control the bus voltage; or combining several of the above techniques.

The above example has illustrated an embodiment of the invention in conjunction with a three-phase switched reluctance drive. It will be appreciated that a switched reluctance system having any number of phases, including only one, could be used.

Other types of machine to which embodiments of the invention are susceptible include stepper motors and some types of single-phase induction motors in which the main and starting windings are independently supplied.

The skilled person will appreciate that variation of the disclosed arrangements are possible without departing from the invention. Accordingly, the above description of several embodiments is made by way of example and not for the purposes of limitation. It will be clear to the skilled person that minor modifications can be made to the arrangements without significant changes to the operation described above. The present invention is intended to be limited only by the scope of the following claims.